STATE OF CALIFORNIA
Department of Transportation
Division of Construction
Office of Transportation Laboratory

CHEMICAL STABILIZATION OF LANDSLIDES

LITERATURE REVIEW AND FIELD TESTING

Interim Report

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16. ABSTRACT

Landslides occur throughout California along state highways. These landslides can pose a safety hazard and are an inconvenience to the traveling public. These landslides are expensive and time-consuming to stabilize using conventional methods.

The initial purpose of this research is to identify chemicals with the potential for stabilizing an area subject to long-term creep. Second, to place the chemicals in the soil and monitor the area to determine the effectiveness of the treatment.

This interim report deals with the first phase of the project, a detailed literature search. Two types of chemicals were identified, resins and silicates.

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The contents of this interim report essentially reflects the work done by the University of California, Berkeley as part of their contract with the California Department of Transportation

CONVERSION FACTORS

English to Metric System (SI) of Measurement

Quality	English unit	Multiply by	To get metric equivalent
Length	inches (in)or(")	25.40 .02540	millimetres (mm) metres (m)
	feet (ft)or(')	.3048	metres (m)
	miles (mi)	1.609	kilometres (km)
Area	square inches (in^2) square feet (ft^2) acres	6.432×10^{-4} .09290 .4047	square metres (m^2) square metres (m^2) hectares (ha)
Volume	gallons (gal) cubic feet (ft^3) cubic years (yd^3)	3.785 .02832 .7646	litre (l) cubic metres (m^3) cubic metres (m^3)
Volume/Time (Flow)	cubic feet per second (ft^3/s	28.317	litres per second 1/s)
	gallons per minute (gal/min)	.06309	litres per second (1/s)
Mass	pounds (lb)	.4536	kilograms (kg)
Velocity	miles per hour (mph) feet per second (fps)	.4470 .3048	metres per second (m/s) metres per second (m/s)
Acceleration	feet per second squared (ft/s^2)	.3048	metres per second squared (m/s^2)
	acceleration due to force of gravity (G) (ft/s^2)	9.807	metres per second squared (m/s^2)
Density	(lb/ft^3)	16.02	kilograms per cubic metre (kg/m^3)
Force	pounds (lbs) (1000 lbs) kips	4.448 4448	newtons (N) newtons (N)
Thermal Energy	British termal unit (BTU)	1055	joules (J)
Mechanical Energy	foot-pounds (ft-lb) foot-kips (ft-k)	1.356 1356	joules (J) joules (J)
Bending Moment or Torque	inch-pounds (in-lbs) foot-pounds (ft-lbs)	.1130 1.356	newton-metres (Nm) newton-metres (Nm)
Pressure	pounds per square inch (psi)	6895	pascals (Pa)
	pounds per square foot (psf)	47.88	pascals (Pa)
Stress Intensity	kips per square inch square root inch ($ksi\sqrt{in}$)	1.0988	mega pascals$\sqrt{metre}$ ($MPa\sqrt{m}$)
	pounds per square inch square root inch ($psi\sqrt{in}$)	1.0988	kilo pascals$\sqrt{metre}$ ($KPa\sqrt{m}$)
Plane Angle	degrees (°)	0.0175	radians (rad)
Temperature	degrees fahrenheit (F)	$\frac{+F - 32}{1.8} = +C$	degrees celsius (°C)

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FINANCIAL DISCLOSURE STATEMENT

The research summarized in the Attachment was jointly funded by the State of California, Department of Transportation (Caltrans) and the Federal Highway Administration (FHWA). The ceiling amount for this contract, RTA 74E344-54F200 is $25,000.

INTRODUCTION

There are numerous landslides in California and Caltrans spends millions of dollars each year stabilizing them. At the present time, most slope instabilities are corrected by removing the slide material, installing a drainage system, replacing and compacting the previously removed material or importing and compacting a higher quality soil. This method is both expensive and time consuming. The object of this research project is twofold, first to stabilize a slope that is subject to long-term creep by using the in situ technique of chemical stabilization. Second, to evaluate the method to determine if it is economically competitive with existing methods.

The research project is divided into two phases. The first phase was to perform a detailed literature search to identify chemicals and processes that could be used and the second is to implement the findings of the literature search. Second phase tasks are to identify one or more sites that are experiencing long-term creep, place the chemicals in the soil, and monitor the sites to determine the effectiveness of the treatments.

This interim report deals with the first phase of the project, the literature search. The literature search was conducted by the Institute of Transportation Studies at the University of California, Berkeley (UCB). The literature search was to identify two specific subject areas. First, to identify chemicals that have the potential for stabilizing slopes experiencing long-term creep. Second, to identify methods of placing the chemicals in the soil. The literature search report contracted by UCB is appended to this interim report as an attachment.

SUMMARY OF CONCLUSIONS FROM UCB REPORT

The literature search revealed a host of information on the use of chemicals for stabilizing soil. However, very little of the information dealt with stabilizing creeping slopes. Most of the information dealt with road bases, erosion control, or decreasing settlement.

Laboratory soil tests using chemicals for stabilizing soils consisted of the following: Atterberg limits, some type of strength test, potential for volume change, moisture-density relationships, water resistance, and resistance to weathering.

Field tests were reported as case histories and were limited to foundations, road bases and tunnel excavations. Specific identification and formulation, properties, cost and availability of the chemicals were not indicated.

SUMMARY OF RECOMMENDATIONS FROM UCB REPORT

The literature search revealed two chemical types that show promise for the stabilization of slopes experiencing creep. They are the following:

- Resins
- Silicates

Both types have been effective in increasing the strength and stability of soil in more than one case. The potential for effective stabilization of an area appears high if these chemicals are well mixed with the soil.

The second objective of the literature search was to identify methods of placing chemicals in the soil. Three techniques were identified for the placing of chemicals in the soil in a well mixed condition. They are the following:

- Jet Grouting
- Deep Chemical Mixing
- Impulse Injection

These techniques are relatively new and need further investigation.

IMPLEMENTATION

The Caltrans Transportation Laboratory will implement the findings of the Phase I literature search.

The current approved proposal will be revised and expanded to describe those tasks that will be performed in Phase II. Once the revised proposal is approved, field work will proceed.

The process of identifying one or more sites that are experiencing long-term creep is in process. The soils will be tested to determine which of the two types of chemicals shows the best promise for stabilization. The three mixing techniques will be investigated to determine which technique works best with the chosen soil and chemicals.

DISCUSSION

Presently, lime and portland cement are additives that are used to stabilize fine-grained soils. The main uses have been for treatment of roadway base courses, erosion control and prevention of settlement. A detailed literature search was conducted looking into lime and portland cement as slope stabilizers. Both lime and portland cement have been used to some extent for the stabilization of slopes and the results have been encouraging. Since both of these products have been shown to be somewhat successful, it was decided to investigate other products for the stabilization of slopes.

A literature search was conducted in-house into the use of chemicals for the stabilization of slopes. Since very little useful information was located, it was felt that this was still an area that needed to be investigated. To further this investigation a contract was awarded to the University of California, Berkeley and this interim report deals with the resulting literature search and recommendations.

The main purpose of this project is to stabilize slopes that are experiencing long-term creep by using chemicals or chemical admixtures. In order to accomplish this, the chemicals injected into the soil must increase the soil shear strength. This is accomplished be either cementing the soil particles together or by increasing the soil cohesion. Also, the reduction of the soil plasticity and an increase in the water resistance are beneficial soil property changes.

In the field of soil stabilization many chemicals have been tried. The chemicals were injected, mixed or allowed to diffuse through the soil. Of the chemical types that were identified, only resins and silicates appear to be applicable to slope stabilization.

Concerning resins, the literature search references provided little specific information or data about the individual resins tested. There are a large number of natural and synthetic resins available for use and one of these resins may be a good candidate for slope stabilization. Resins can be used in sandy and clayey soils. They can bring about an increase in strength and a reduction in swelling. Resins have an advantage of a faster rate of setup than many other chemicals. A drawback to the use of resins is their high cost.

Sodium silicates work to stabilize a soil in the same fashion as resins, by filling the pores of the soil and cementing the soil particles. Again, the literature search revealed little information on the compositions of the silicates viewed as promising for slope stabilization.

Diffusion rates of chemicals in soils are very slow; therefore, it is not reasonable to expect that a critical mass of soil can be permeated by diffusion alone. The literature search uncovered three techniques forthe placement of chemicals in the soil to achieve a well mixed condition.

Deep chemical mixing, jet grouting and impulse injection are processes that can be used for the placement of chemicals in the soil in a well mixed state.

Deep chemical mixing is an in situ process whereby an admixture is mixed with the soil to form stabilized columns or walls. A measured amount of stabilizer is placed into the soil through rotary drills equipped with special bits that mix the chemical and the soil thoroughly. The process can be used alone or with other stabilization methods. The necessary factor of safety can be achieved by an arrangement of individual columns, groups of columns, in situ walls, or treated buttresses.

Jet grouting is a technique that fractures and erodes the soil around a drilled hole by high pressure jets directed horizontally away from the drill rod. The chemical is injected through the drill rod and mixed with the disturbed soil to form columns of stabilized soil. This method can be used vertically or at an angle to stabilize a slope.

Impulse injection is a rapid series of pulsed injections under very high pressure that is used to mix a chemical stabilizer with the soil. The injected material breaks down the soil and mixes with it to form a high strength area.

Appendix 1 is a copy of the letter sent for the solicitation of information on chemical stabilization of slopes.

Appendix 2 is a list of manufacturers and distributors of proprietary chemical stabilizers.

Appendix 3 is a listing of sources for resins and silicaes. The listed companies should be able to provide information about compositions, properties, handling, environmental impacts, availability and costs of the chemicals. These companies will be contacted as part of Phase II work.

Appendix 4 lists organizations that are involved in deep mixing, jet grouting and impulse injection. These companies will also be contacted as part of Phase II.

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(partial list)

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Note: The attachment to this report contains an exhaustive reference list on chemical stabilization of soils.

ATTACHMENT

Chemical Stabilization of Landslides

Literature Review

Contents

Institute of Transportation Studies
University of California, Berkeley

Chemical Stabilization of Landslides

James K. Mitchell
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CHEMICAL STABILIZATION OF LANDSLIDES

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Final Report

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NOTICE

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INTRODUCTION

A. Statement of Problem

Unstable and creeping slopes along and adjacent to California highway rights of way pose immediate and continuing problems in highway maintenance for the California Department of Transportation. The results of a comprehensive literature evaluation of promising chemical additives and methods for stabilization of landslides that might help mitigate this problem are presented in this report. Lime and portland cement, the most widely used admixtures for soil stabilization, were excluded from this study, except where referred to for comparison purposes.

Field testing of chemical slope stabilization is to be undertaken by Caltrans using the results of this study. Important considerations in the design of a field test program are indicated.

B. Method of Investigation

This evaluation of chemical additives and methods is based on information in the literature available to the authors. Relevant reports, articles, and papers were reviewed that were available from the libraries at the University of California, Berkeley and personal files.

In addition, information regarding specific chemical soil stabilizers was obtained through personal contacts with companies marketing special products. Finally, the Geotechnical Engineer of the Department of Transportation of each state and of each Federal Highway Administration Region was contacted and informed of the investigation and asked to forward any pertinent information. A copy of the letters used for these contacts and a summary of the results of the solicitation are given in Appendix 1. Unfortunately, while many of the individuals who were contacted responded, few had any personal experience or information about the use of chemicals for slope stabilization.

CONCLUSIONS

Much information on the stabilization of soils using chemicals is available in the literature. However, little concerns chemical stabilization of landslides and natural slopes. Most of it deals with the stabilization of soils for use in road bases, erosion control, the prevention of settlement of structures, and, to a lesser extent, with the stabilization of cuts/excavations.

The few references specific to landslide stabilization concerned ion exchange, injection of chemicals, and grouting of hillsides. Very few tests have been performed in the laboratory to study the stabilization of slopes; results presented were either from field tests or from case histories.

Soil stabilization chemicals that have been studied most in the laboratory include phosphoric acid, salts, resins, sodium silicate, lignin, organic cations, and hydroxides. Laboratory tests for the evaluation of their effectiveness generally included one or more of the following: Atterberg limits, some type of strength test, potential for volume change control, determination of moisture-density relationships, water resistance tests, and resistance to weathering (freeze/thaw, wet/dry). Chemicals were most often mixed with or injected into the soil, with the resulting material compacted to make test samples of the soil-chemical mixture. A wide range of soil types was tested, including clays, silts, loesses, loams, tills, sands, and gravels.

Field tests were generally on roads that incorporated sections of stabilized soil. In situ strength tests, resistance to weathering, and penetration tests were some of the evaluation procedures used in the field.

Case histories described in the literature included the chemical stabilization of foundations, road bases, and a few tunnel excavations. In most cases specific identification and formulation, properties, cost, and availability of the chemicals were not indicated. The toxicity or other potential environmental impacts of the chemicals were not stated, and in most cases they are probably unknown.

RECOMMENDATIONS:

A. Most Suitable Chemicals

Despite the large number and variety of chemicals that have been proposed for soil stabilization, only a few, other than portland cement and lime, have shown promise for the stabilization of slopes. Based on available laboratory and field test results, the materials with the greatest potential applicability appear to be:

1. resins
2. silicates

Both resins and silicates proved effective in increasing the strength and overall stability of soil in more than one case. The potential for stabilization of slopes with either of these two materials appears high if they are mixed well with the soil. Whether they will be effective if simply injected into the soil mass without intimate mixing depends on whether they permeate the shear zone or migrate along the shear plane.

Other chemicals that appeared promising in at least one test include aluminum hydroxide, calcium hydroxide, fatty acid amine acetate, gypsum/slag, poly aluminum chloride, and cement grout.

A few of the proprietary products suggested by manufacturers appear to have some potential for the stabilization of slopes. A sulfonated oil product and a system involving several unspecified chemical compounds, the Claypak system, may be promising.

Finally, three relatively new techniques should be considered for slope stabilization. Jet grouting, deep chemical mixing, and impulse injection are processes that can be used to mix a chemical with the soil in situ.

B. Guidelines for Method Suitability

A chemical stabilization method can be considered suitable technically if it can be demonstrated that the strength and durability of the treated soil will be sufficient to insure adequate slope stability over the long term. By durability is meant the resistance of the treated soil to strength loss due to potential adverse effects of wetting, drying, freezing, thawing, leaching, or chemical and biological processes of degradation.

Strength improvement and the short term resistance to property degradation due to some of these factors are readily evaluated by laboratory tests. Test programs of the type used for assessment of the strength and stability of stabilized soils used for other purposes, e.g., pavement bases and subgrades, can be used. Consideration must be given, however, to use of representative treatment levels, densities, water contents, confining pressures, and access to water.

The long-term durability is less easily determined. Although the results of accelerated weathering and cyclic loading tests in the laboratory are useful indicators, the most useful and reliable information will be provided by continued observation of the performance of the field test section. These observations should be accompanied by periodic in situ measurements of properties or sampling and laboratory testing.

The practical suitability of a method will depend on there being available equipment and procedures that will enable getting the proper amount of stabilizer to the right place at the right time. The surest way to do this would be to excavate the slope, mix the soil with the stabilizer, and recompact the slope. The practicality and economics of doing this are prohibitive in most cases. Accordingly, other techniques for injection and mixing in-place must be considered, and they are considered later in this report.

The environmental suitability of a chemical method must be evaluated. Unfortunately, the literature on chemical stabilization of soils does not include much information on toxicity or other possible adverse environmental impacts, although such information is available for some of the chemical grouts. Prior to field tests of a chemical stabilizer it will be necessary to satisfy all relevant environmental regulations pertaining to protection of workmen, groundwater, etc.

Finally, the economic suitability of a proposed chemical stabilization must be determined. Chemical stabilization is but one of several methods that may be considered in any case.

C. Possible Field Tests

Unambiguous evaluation of a chemical slope stabilizer in the field will be a challenging undertaking. Great care will be needed in the selection of a suitable site, evaluation and documentation of initial conditions, design and control of the test sections, execution of the stabilization, and monitoring of subsequent environmental conditions and slope performance.

Regardless of the chemicals or sites chosen, it is essential that the stabilizer be incorporated within the soil regions where deformation and/or failure are taking place. Although the preceding statement would seem obvious, locating the shear zones and insuring a suitable distribution of the chemical are likely to be the two most limiting factors in the effective stabilization of a slope.

Diffusion rates of chemicals in soils are very slow, on the order of only a few inches per year for simple, small ions, and less than this for large molecules. Accordingly, it is not reasonable to expect that a critical mass of soil can be permeated by diffusion alone. Thus, the simple injection of chemicals in the hope that they might migrate throughout a deforming mass of fine-grained soil is unrealistic. Similarly, permeation grouting; i.e., the filling of voids in a soil with chemical grout, becomes difficult when the soil contains more than about 12 percent fines and impossible when the fines content is greater than about 20 percent.

Techniques are now available for jet grouting and deep chemical mixing by which stabilizing chemicals can be mixed in situ with the soil. This extends greatly the range for successful in situ chemical stabilization beyond the permeation grouting of coarse-grained soils and encapsulation grouting of fissured soils that has been possible heretofore.

The new techniques make it possible to form columns, walls, and buttresses of strengthened soil. If the properties of the untreated and treated soil are known, it is then possible to design systems to bring the slopes to acceptable factors of safety. The new technologies are described both in the technical literature and in literature provided by the specialty contractors who have the equipment necessary to do the work. Brief descriptions are given in a later section of this report.

The detailed design of a specific field test is beyond the scope of this report. It is possible, however, to list criteria that must be considered in order to optimize the possibilities for a definitive evaluation of a chemical slope stabilization field test. The following aspects must be considered carefully:

1. Site selection

   A site should be selected where an existing slope is undergoing measurable creep or is at a state of incipient failure. A relatively homogeneous soil profile, or a profile with a clearly defined shear zone is preferred. The soils should be fine-grained, or there should be enough fines that stabilization is not possible by simple grouting. The site should be of sufficient size and geometry so that side-by-side sections of treated and untreated soil can be compared. Groundwater conditions should be known, and there should be reasonable expectation that if a normal winter follows the start of the test, then the untreated section will either fail or there will be accelerated creep movements.

2. Evaluation of initial conditions

   A complete set of field and laboratory tests should be done so that the profile, soil properties, and water table conditions can be accurately defined.

3. Selection of chemical stabilizer

A material from among the resins or silicates should be chosen on the basis of a suitable laboratory testing program using the proposed chemical formulation and soil samples that are representative of both the solid and fluid phases in the field. It is essential that the strength and deformation properties of the soil treated to a level that can be reasonably expected in the field be determined.

4. Design of treatment program

Analyses should be made to determine the amount of soil that must be treated. The geometry of the treated zones; e.g., piles, piers, walls, buttresses, should be decided. The location and distribution of these strengthened elements can be selected, using appropriate stability analyses, so as to give an appropriate factor of safety.

5. Construction procedures

The construction procedures should be defined in advance. Some field testing may be needed to evaluate the applicability of new mix-in-place or special grouting technologies. Samples of the treated soil should be taken during construction to verify that the specified properties are being attained.

6. Instrumentation

Both the treated and untreated test sections should be instrumented with piezometers for measurement of water levels and slope indicators for measurement of profiles through the deforming ground. Surface survey monitoring points should be placed.

7. Monitoring

   The instrumentation should be read on a regular basis, and the data should be evaluated as it comes in so as to maintain a real time assessment of the field performance.

8. Evaluation

   Comparison of the movements recorded in the treated and untreated test sections should provide an indication of the overall effectiveness of the stabilization. Sampling of the treated and untreated soil at the end of the test will provide a basis for final evaluation of soil properties.

BACKGROUND ON LANDSLIDES

A. Introduction

A landslide can be classified in one of three categories:

1. Downslope movement of surface deposits, including talus creep, sheet slides, earth flows, and debris flows.
2. Landslides of soil along rotational sliding surfaces (slumping), movement along composite sliding surfaces, and the squeezing out of soft rock.
3. Rock slides.

The California Department of Transportation is interested in stabilizing hillside movements due both to creep and to failures along rotational and composite slide planes.

B. Creep Phenomena

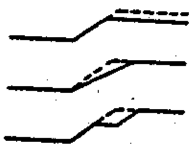
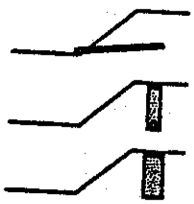
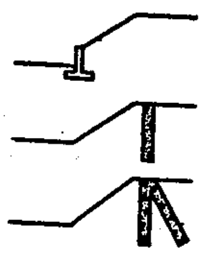
The phenomenon of creep occurs when surface layers of clayey material move downhill as the result of slow plastic deformation. Surface movement rates are usually a few millimeters to a few centimeters per year. No discrete slide plane develops, but rather a broad zone within which small movements occur is formed, making stabilization difficult. Motion is restricted to a relatively shallow surface layer that may not exceed the depth of seasonal variations in temperature and moisture.

C. Landslide Correction

Correcting landslides (Table 1) involves preventing the movement of the soil mass by (1) construction of barriers able to resist the downslope forces and/or (2) reducing the forces tending to cause the movements. Techniques used to do this include improved drainage, construction of retaining walls, installation of pile and sheet pile walls, treatment of the slope conformation, and the application of special methods. Strengthening the soil by such methods as electro-osmosis, thermal treatment (heating or freezing), grouting, and chemical treatment fall in the category of special methods.

Very little has been done using chemicals other than portland cement and lime for landslide and creeping hillside stabilization. Satisfactory chemical treatment appears possible, however, for strengthening marginally stable slopes, slopes subject to creep, and for slides and slumps where the shear failure surface can be located.

TABLE 1 METHODS OF STABILIZING SLOPES AND LANDSLIDES

Scheme	Applicable Methods	Comments
I. Excavation 	1. Reduce slope height by excavation at top of slope. 2. Flatten the slope angle. 3. Excavate a bench in upper part of slope. 4. Excavate the entire slide mass.	Area has to be accessible to construction equipment. Disposal site needed for excavated soil. Drainage sometimes incorporated in this method.
II. Drainage 	1. Small diameter, horizontal drains (hydraugers).	1. Most effective if can tap natural aquifer. Drains are usually free-flowing.
	2. Continuous deep subdrain trench. Generally 3 to 15 ft deep.	2. Trench bottom should be sloped to drain and be tapped with an outlet pipe. Perforated pipe should be placed on trench bottom. Top of trench should be capped with impervious material.
	3. Drilled vertical wells - generally 18- to 36-in. diameter.	3. Can be pumped or tapped with a gravity outlet. Several wells in a row, joined at bottom can form a drainage gallery. Top of each well should be capped with impervious material.
	4. Improve surface drainage along top of slope with open ditch or paved gutter. Install deep-rooted, erosion-resistant plants on slope face.	4. Good practice for most slopes. Direct the discharge away from slide mass.
III. Earth or rock buttress (or berm fill) 	1. Excavate slide mass and replace with compacted earth or rock buttress fill. Toe of buttress must be keyed into firm soil or rock below slide plane. Drain blanket with gravity flow outlet is provided in back slope of buttress fill.	1. Access for construction equipment and temporary stockpile area required. Excavated soil can usually be used in fill. Underpinning of existing structures may be required. Might have to be done in short sections if stability during construction is critical.
	2. Compacted earth or rock berm placed at and beyond the toe. Drainage may be provided behind berm.	2. Sufficient width and thickness of berm required so failure will not occur below or through berm.
IV. Retaining structures 	1. Retaining wall - crib or cantilever type.	1. Usually expensive. Cantilever walls might have to be tied back.
	2. Drilled, cast-in-place vertical piles, bottomed well below bottom of slide plane. Generally 18 to 36 in. in diameter and 4- to 8-ft spacing.	2. Spacing should be such that soil can arch between piles. Grade beam can be used to tie piles together. Very large diameter (6 ft ±) piles have been used for deep slides.
	3. Drilled, cast-in-place vertical piles tied back with battered piles or a deadman. Piles bottomed well below slide plane. Generally 12 to 30 in. in diameter and at 4- to 8-ft spacing.	3. Space close enough so soil will arch between piles. Piles can be tied together with grade beam.
	4. Earth anchors and rock bolts.	4. Can be used for high slopes, and in very limited areas. Conservative design should be used, especially for permanent support.
	5. Reinforced earth.	5. Usually expensive.
V. Special techniques	1. Grouting 2. Chemical injection	1. and 2. Used successfully in a number of cases. Used at other times with little success. At the present, theory is not completely understood.
	3. Electroosmosis (in fine-grained soils).	3. Generally expensive.
	4. Freezing 5. Heating	4. and 5. Special methods which must be specifically evaluated at each site. Can be expensive.
		All of these techniques should be carefully evaluated in advance to determine the probable cost and effectiveness.

(From W. J. Turnbull and M. J. Hvorslev, "Special Problems in Slope Stability," Journal, Soil Mechanics and Foundations Division, ASCE, Vol. 93, No. SM4, 1967, pp. 499-528.)

LITERATURE SURVEY AND DISCUSSION

A. Introduction

In the past the primary additives used for the stabilization of fine-grained soils were lime and Portland cement. Primary applications have been for treatment of pavement subgrades and base courses. Neither of these materials nor other chemicals have seen wide application for slope stabilization. However, injection of cement and chemical grouts has been used successfully for soil strengthening in a number of cases.

To stabilize a hillside, the chemicals must affect the soils so as to maintain or increase the shear strength, either by cementing the soil particles and/or by giving the soil cohesion. In addition, reduction of the plasticity and an increase in the water resistance of a soil are desirable property changes.

Lime columns and mix-in-place piles and walls have been developed in recent years, and they may find wide application in the future. In addition, techniques for jet grouting are now available. These new developments, described in more detail later in this report and in Reference No. 55 provide a means for mixing the stabilizer with the soil and for treatment of clearly defined zones. Thus, it is now possible to design a stabilization such that if the specified geometry and treated soil strength are obtained, a reasonable evaluation of the new factor of safety will be possible.

B. Summary of Literature on Chemical Stabilization of Soils

The references appended to this report list all of the papers, reports and other articles reviewed for this study. Each reference is listed alphabetically by author and again numerically by accession number.

The latter listing will be useful to readers who wish to quickly identify a reference corresponding to an entry in Table 2 or to call up the information from the computer data base assembled during this project.

Several keyword numbers have been assigned to each reference to provide a rapid assessment of its contents. The keywords are listed both alphabetically and numerically preceding the reference lists.

Table 2 contains a comprehensive summary of all the reviewed information from the literature, organized by chemical class; e.g., salts, resins, hydroxides, acids, polymers, etc. To the extent that the information and data were available, the following entries are given for each chemical tested or proposed as a soil stabilizer:

1. Chemical
2. Treatment level - percent, by weight of dry soil, in most cases
3. Soil type
4. Soil state - except for grouting studies, most investigations were made using compacted specimens of treated soil
5. Laboratory tests - an X indicates laboratory tests used for evaluation
6. Field tests - an X indicates field tests used for evaluation
7. Test type - type of test used to evaluate stabilizer
8. Cure time - Time between soil treatment and testing
9. Method of application - means for incorporation of stabilizer with soil
10. Test results - brief summary of most important test results
11. Author's Comments - summary of the main conclusions and recommendations given by the author(s) of the indicated reference

12. Slope stabilization potential - this is an opinion by the authors of the present report (Mitchell and Klainer)

13. Reference number - see numerical listing of references for complete citation.

A listing of the abbreviations used in Table 2 follows the table. A separate listing of all the proprietary chemicals and stabilization systems that have been reviewed relative to suitability for slope stabilization is given in Table 3. Addresses for the manufacturers or distributors of these products and the names of company contacts are indicated in Appendix 2.

Interaction between the soil to be stabilized and resins consists of either the binding of the soil particles by the resin or the filling of the voids in the soil structure. Resins can be either mixed with the soil or injected into it to create a stabilized material.

C. Non-Proprietary Chemical Techniques for Soil Stabilization (Table 2)

Many chemicals have been tried for soil stabilization. They have been either mixed with, injected into or allowed to diffuse through the soil samples. Of those listed in Table 2 only the resins and silicates would appear to have general applicability.

Unfortunately, the references provide little specific information or data about the particular resins tested, and a wide range of materials has been studied. A large number of natural and synthetic resins and resin-like materials is available. Acrylamides, liqnosulfites, phenoplasts, aminoplasts, urethanes, epoxies, and polyesters have all been used in chemical grouting, and one of these materials may be a good candidate for slope stabilization. Since direct mixing of the chemical and soil is regarded as

TABLE 2 SUMMARY OF LITERATURE ON CHEMICAL STABILIZATION OF SOIL

(Abbreviations are defined at end of table)

AMINES

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
quat amines; 4 TBC;		?	compacted			AL; uncon compression; volume change; moisture-density		mixed	none found effective for highway soils;	properties of concern=plasticity, strength, density, volume chanted due to moisture changes; no single chemical or combo effective as soil stabilizer; work as supplements to PC & lime	low	25
fatty acid amine acetate	AL: .5,1,2% dry wt of soil; m-d,CBR: % to reduce PI to 3	2 soil-aggregate mixtures		X		AL; shrinkage limit; m-d; CBR; swell potential	4 days imm	mixed	3% caused PI to decr; shrinkage decr; dmax & wopt decr; unimm CBR decr, imm incr; swell decr	no test of permanency of organic cation treatment performed; studied only mixing - need to investigate other application methods; more research needed, however, fatty acid amine acetate shows promise		89
cations: 6 soluble organic cmpds	up to 80% saturation base exchg capacity	Edina subsoil	air dried pats	X		AL; shrinkage limit; slaking rate; air-dry str (soil penetrometer)		mixed	PI decr to a pt; shrinkage limit incr; time to slake incr; str decr	gen desirable stab method, except for strength loss; 2 compounds merit further study: Armac T, Rosin Amine-D Acetate	inject: low mix: ?	88
fatty acid amine acetate	.5,1,3% dry soil wt XX to reduce PI 3	2 base course materials		X		AL & Shrinkage (SOIL A); find X% to get PI to 3; moisture-density & CBR (SOILS A & B)		mixed	PI decr; shrinkage (both soils) decr; wopt decr, dmax incr; unsoaked CBR decr; soaked CBR incr	further study needed but work so far indicates promise as stabilizing agent; no tests on permanency of treatment performed	inject: ? mix: high?	118

BITUMENS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
cutback asphalt + metallic salts	1,2% salt; 0-4% salt + fixed amt asph	various hydrophilic soils	aggregates	X		asphalt adhesion; modified bearing values; capillary water absorption		mixed	adhesion incr; gen MBV incr to a pt for all soils	no stabilization with salt alone; adding dry salt = same results as adding salt in solution; cannot apply lab results to practice, must do road test strips; economically feasible to use salts and cutback asphalt	low	19
bitum+a-f; &+Ca(OH)2; &+tall oil	8,10% bitum + .06-.24% a-f; + 2.5,10% tall oil (dry soil wt)	clay	compacted	X		compressive str; cure method	7 days wet & 7 days dry		dry cure str > wet cure str; weathering resistance incr; str incr, density incr	poor performance of moist-cured samples in fr/th conditions; dry cure str > wet cure str after w/d, fr/th cycles		72

CATIONS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
organic cations	0-80% sat base exchng capacity	clay	pats, compacted	X		AL; shrinkage limit; str tests; slaking		mixed	PI decr; shrinkage limit incr; air dry str decr (cohesion decr); water resis incr	strength decrease a problem if using this treatment otherwise a promising treatment		120
exchangeable cations		cohesive							soil aggregates	hydroxides with K+, Ca++, Mg++ discussed; no lab data	?	31
large org cationic mat'l + polyacid;	.2% oc + .6% pa	silty loam; loess	compacted	X		uncon compression	7 days; 7 days + 24 hrs imm	mixed	no polyacid: unimm str decr, imm str incr to .2%; polyacid alone: slaked in water, unimm str incr; both: str incr;	polyacid effectiveness = f(molecular wt); cation-hydroxide better than cation-chloride + polyacids; if use cation + polyacid, no maximum limit of cation percentage reached; addition of ferric compounds being investigated	?	93

HYDROXIDES

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
OH-Al		clay		X		fallcone	up to 100 days (diff)	ion diff & mixed	str incr	comparison betw lab and field test difficult;	inject: low mix: high	2
OH-Al		quick clay	in situ		X	direct shear; uncon compression; bending	2 mos	mixed-clay cols in situ	??	incomplete mixing in field		
OH-Al+KCl		"	"		X		"	"		OH-Al comments: expensive, can stabilize all clays with necessary additives; higher strengths than CaO in lab; lower or same str		
various cmpds		various clays		X		uncon compression		mixed	depends on which clay	as CaO in field		
calcium hydroxide	5% by wt	various soils	natural soil aggregates	X		potential volume change; AL; mineralogical anal	up to 1 yr	mixed	gen swelling pressure decr; PI decr; mineralogical changes	greatest changes in montmorillonite clay soils	inject: low mix: high	103
hydroxides (Li,Ba,Ca, Na,K,ammon);	up to 100% dry oven wt	kaolinite; montmorillonite	compacted	X		uncon compression or indirect tension test	up to 2 yrs	mixed	kaol: LiOH: no str chng, vol incr Ba,CaOH: sm str incr w/const w, no vol chng w/incr w; Na,KOH: str incr after init decr; AmmOH: str decr; HFa: no str chng; Pa: no str chng, no reaction; Aa: str decr; mont: Li,BaOH: str incr, vol incr; CaOH: str incr (more time than BaOH-1 mo vs 24 hrs); K,NaOH: str decr permanent, vol	need a water insoluble result in soil-chemical mixture; pH is an important consideration;	low	26
hydroxy-aluminum solutions		natural sandstone	cored sample & in situ	X	X	permeability	20 min, 2 days, 7 days	sample flooded	less perm damage when OH-Al used; fresh water sensitivity decr	want to inhibit perm damage due to clay expansion; study clay dispersion and perm of rock; incr aging in fresh water beneficial	?	74

HYDROXIDES (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref No.
hydroxides;		expansive silty clay		x		AL; torsion vane; weathering by leaching	up to 150 days	mixed or diffused	hydroxides: Ba,Ca,K cause str incr, exp decr; Ca insoluble; Na cause shear str & exp incr;	Further investigation should focus particularly on chemicals that cause shear str to incr before and after neutralization/leaching (weathering): These tests should include: 1. opt application rate 2. reaction products formed 3. nature of stab mechanism 4. permeability changes 5. methods of application 6. most economical chemicals 7. results w/other shear str tests 8. rates of diffusion of chem thru soil 9. adverse environmt'l consequences etc.	low	70

LIGNINS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
lignosol	1.2, 2%	gravel w/clay	compacted	X		bearing capacity; uncon compr; water absorption		sprayed, mixed & injected	bearing capacity incr; compressive str incr; cap abso decr	increase in strength proportional to increase in % lignosol; susceptibility to frost decr; solubility in water could be a problem, but hard to test		117
lignin + protein-cation complexes	.5, 2% lignin	silty loam		X		strength test			tr samples slaked in water			121
Ca-ligno-sulfonate + Al-sulfate	0,2,4,6,8% Ca-l & 0,1,3,5% Al-s	loess	compacted	X		mixing order; uncon compression; expansion; freeze/thaw; different cure conditions; m-d	7 days; 7 days + 24 hrs imm	mixed	Ca-l 1st, Al-s 2nd chosen as best order; str incr to a point, opt = 6% Ca-l, 8.5% Al-s; freeze/thaw makes str decr	degree of stabilization = f(atmospheric conditions during cure); humidity causes str to decrease	?	94
lignin liq. + hexavalent chromium salts		sand; silt; clay		X					silts: most str incr; can make soils imperm.	difficult to use in field, good for soil briquettes, can stabilize wide variety of soils	low	51
lignin				X					previous tests w/Fe, Ca-Cr lignin: soil disperses, str incr	abstract of current studies; results mentioned from previous research: Fe lignin had dispersive effect on soil, Ca-Cr lignin gives soil high str	?	82
lignosulf;		?	compacted			AL; uncon compression; volume change; moisture-density		mixed	none found effective for highway soils;	properties of concern=plasticity, strength, density, volume chanted due to moisture changes; no single chemical or combo effective as soil stabilizer; work as supplements to PC & lime	low	25
lignosul-onates;	.5-2%	soil aggregate mix: glac till + gravel + silty clay loam	compacted	X		moisture-density; CBR; AL; moisture retention	m-d 5 min CBR immed & 4 days imm	mixed	gen dmax incr (CaCl, mol opt at 1%); str incr for CaCl, lign; PI changed from mol and lig	recommendations to continue studies; cannot directly compare results of moisture retention for different chemicals;	low	40

MISCELLANEOUS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref No.
poly-alum. chloride& iron pwdrs (Al^{3+},Fe^{3+})		marine clay	compacted	X		uncon compression; vane shear; compressibility	1 day, 1 week, 1 mo, 3 mos, etc	mixed	shear str incr as amt cations & time incr; yielding load in comp test incr	need to establish construction technique for mixing additives; maybe use as additive with lime	inject: low mix: high in soft clay	52
gypsum & granulated slag + (PC or lime)	10 & 20% by wt of dry soil (total trtmt)	cohesive & sandy soils	compacted	X		compressive strength	3,7,28,90, 180 days	mixed	cohesive: more gyp = more str at earlier ages; sandy: lower str earlier		inject: low mix: high?	20
unspecified	7% chem soln	clay	compacted	X		1D compression	up to 130 hrs	immersed (diffusion)	% swell decr	need extensive sampling to determine approp chemicals; in situ placement through drilled holes or tension cracks	?	78
			remolded	X		vane shear	up to 70 days	mixed	gen strength incr			
Na tetra-phosphate	.1 -1 % of dry soil wt	clay, silt		X		unspecified		injected	uncon comp str same; compact to denser state; perm decr	increases effectiveness of PC	?	23
	.1 %	clay	in situ		X	membrane-soil blanket		mixed	leakage of contaminate decr			
cement grout		saturated clays	in situ		X	prevention of movement of landslide		injected	success in many cases	stabilization mechanism unknown; doesn't penetrate voids of clay; general paper--case histories mentioned	inject: ? mix: high	14
unspecified chems for ion exchge		sat clay soil	in situ		X	stab of landslide		injected	SI's show same mvemt before and after trtmt;	only limited data so must be careful interpreting results; recommend another test using this stabilization method	none unless chemicals id'd	87
		sample from field		X		vane shear str; uncon compression	1 yr	"	gen vane shear str incr below 20 ft; uncon comp str incr & decr			
TBC	.05 - .425%	unspecified	compacted	X		unconfined compr	7 days + 1 day imm	emulsion in molding water	strength incr	TBC reduces absorption of water by soil; compact immediately after treatmt; silty soils best; only keeps water out	low	71
						freeze-thaw	3 days 100% RH 4 days 30% RH					

MISCELLANEOUS (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
chlorides; fluorides; phosphates; sulfates; org chems; other chems		expansive silty clay		X		AL; torsion vane; weathering by leaching	up to 150 days	mixed or diffused	chlorides: LL decr; shear str decr then incr; as at low w, decr at high w; flourides: rapid str incr at all w; insoluble, so no leaching during weath; phosphates: str incr at low w, incr more after weath; sulfates: ammon, Ca no effect; Al str incr at low w; Fe str & LL incr; org chem: str incr only if w low; not resis to leaching; other chem: Kiodide bad; FeO bad; Al nitrate str incr or decr; etc.	HF expensive and hard to handle; Acidic phosphates show promise; Resultes depend on water content and degree of weathering; Further investigation should focus particularly on chemicals that cause shear str to incr before and after neutralization/leaching (weathering): HF, KF, NaOH, Phos acid, Ca phosphate, Na metasilicate These tests should include: 1. opt application rate 2. reaction products formed 3. nature of stab mechanism 4. permeability changes 5. methods of application 6. most economical chemicals 7. results w/other shear str tests 8. rates of diffusion of chem thru soil 9. adverse environmt'l consequences etc.	low ? ? ? low ?	70
tung oil		sandy loam;	compacted	X		strength; water resistance;	air dry + imm	"	needs 4 days to cure, good when immersed;	further, more systematic studies of the more promising chemicals advised;		97
linseed oil	up to 10%	"	"	X		"	"	"	not as effective as tung oil	must look at economics; need to study bonding and waterproofing agents		
nitric acid; sulfuric ac; hydrofluoric acid	2,5,10%	5: silty sand, clayey silt, sandy clay, loess, buckshot clay	compacted	X		uncon compr	var times, + imm	mixed	str incr w/incr cure time; water resis incr; d incr	stability decreased with increasing fineness of soil; more strength developed on humid cure specimens than on dry cure ones; costs discussed nitric and hydrofluoric acids not as effective as phosphoric, sulfuric acid ineffective		119
ammonia alkili soln;	3,5,7%	loess soils		X		compression	28 days, 6 mos 24 mos	soaked	compr decr; less compr than untr;	loess can be stabilized w/out introducing a binder	inject: ? mix: high (silty soils)	59
acids (phos, hydroflour, acetic)	up to 100% dry oven wt	kaolinite;	compacted	X		uncon compression or indirect tension test	up to 2 yrs	mixed	kaol: HFa: no str chng; Pa: no str chng, no reaction; Aa: str decr;	need a water insoluble result in soil-chemical mixture; pH is an important consideration;	low	26

PHOSPHORIC ACID

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
phosphoric acid + Al sulfate;	.6-4% pa + 1-3% Als	till		X		strength;	14 days + 24 hrs imm		str incr to certain point;			42
phosphoric acid	1-18%	various	compacted	X		uncon compression	7,14,28 days & + 24 hrs imm		uninm str incr w/incr in cure time to 2-10% pa; gen, imm str incr w/cure time incr			42
phosphoric acid w/& w/o amine	2% pa, .5% amine	?, 33% clay	compacted	X		uncon compression; volume change	48 hr imm; 5 day, 2 wks, 1 mo + 48 hr imm	mixed	imm str incr w/incr cure time; vol change very small	strength of cured soil dependent on cure time before immersion; higher strengths for higher compactive efforts; further lab investigation continuing	inject: ? mix: ?	91
		"	"		X	sample buried outdoors to test for winter resistance	6 mos; 1 yr	"	treated were winter resistant, untr became mushy			
phosphoric acid	1-4% dry soil wt	clays; clay loams	compacted	X		AL; compaction; uncon compression; volume change	5 days " 5 days + 2 imm & 5+ 30 imm	mixed	PI decr, d,wopt shift; 20 imm: linear incr str up to 2% pa; 300 imm: linear incr str up to 5% pa; volume change decr	soils high in silt, low in clay not well stab with phos acid alone; unsoaked str>immersed str; the need to cure is apparent - i.e. need time for reaction to take place	inject: ? mix: ?	67
phosporic acid	.5 - 2%	micaceous soils	compacted	X		compressive strength test	7 days + 1 day imm			not as effective as PC or lime due to high amt of kaolins and slow & incomplete reactions	limited	44
phosphoric acid	0 - 2 %	2 clayey silty sand, silty clayey sand, sand, silty sandy clay	all compacted	X		uncon compression triaxial	7,28 days	mixed	wopt no change dmax incr strength incr	more strength gain for finer grained soil; higher % of p.a. gave better results	inject: ? mix: ?	
rock phos+ acid; phos acid+ acid; phos acid+ Fe,Al salts		various	compacted	X		uncon compression; pH	6 days + 24 hr imm immed & 6 days	mixed	r phos: str incr; higher resid pH of soil propor to higher str of treated soil; pa+salts: str incr	acid:phosphate ratio significant to efficacy of treatment; sulfuric better than hydrofluoric acid; phosphoric acid+acid result in best solidification	impractical?	5

PHOSPHORIC ACID (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
phosphoric acid + additives;	2,5,10%	5: silty sand, clayey silt, sandy clay, loess, buckshot clay	compacted	X		uncon compr	var times, + imm	mixed	str incr w/incr cure time; water resis incr; d incr	stability decreased with increasing fineness of soil; more strength developed on humid cure specimens than on dry cure ones; costs discussed additives: amines, flourides		119
phosphoric acid	1-4% pa & 2% pa + .5% amine 2% by dry wt	silt loam	compacted	X				mixed	PI decr; wopt decr; dmax incr; soaked str		?	8
		"			X	field test pilot; proctor needle pen	immed & 2 mos	"	pen resis incr; not much weathering of exposed treated areas	limestone present in field test pilot killed effects of acid to some degree; 2 mile test project planned for 1961-2; promising for stab of heavy clay soils; avoid lime, basic soils		
phosphoric acid + additives		plastic loess	compacted	X		m-d; uncon compression;	7 days + 24 hrs imm	mixed	determinatn of -w plots and str-w plots for each mixture, then str-% pa plot;	montmorillonitic soils show most str gain, immer or unimmer; CaCO3 in soils may limit the use of phosphoric acid;	inject: low mix: ?	42
						cure method comparison;	a) 7,14 or 24 D + 24 hr imm OR b) 7,14 or 24 D+7D+24 hr imm		1st cure opt chosen; 2nd made samples slake when imm;	phosphoric acid may not end up being economically feasible		
phosphoric acid + amines	1,2,3% pa alone & + .5% amines	clay	compacted	X		AL;	8 days	mixed	no amines: gen PI decr; dmax, wopt no chng;	if calcium carbonate present, effectiveness of phosphoric acid decreases; pa cause str incr in 2 of 6 soils tested	?	6
						uncon compression	5 days + 2 imm.		str incr, vol decr; amines: str incr, LL decr			
phosphoric acid	.2-5% by wt dry soil	loess soils	compacted	X		pinhole; uncon compression	7days	mixed	wopt decr, dmax incr, erosn resis incr; str incr-max unimm str at 5% pa	higher clay content requires more pa; need more research: immersed str, repetition of tests performed, swellability, longterm durability;	inject: low mix: ?	16
	.75%	"	"		X	placemt of treated fill		mixed	failure of fill halted	need thorough mixing; not always cost effective		

POLYMERS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
polymers (single & double combos)		sands	compacted	X		erosion control; permeability; unconfined compr; freeze-thaw;	7 days	percolated or mixed	gen perm decr; UV light had no effect; amt to control wind erosn <amt to contr water erosn	polymers that provide good erosion control do not necess provide high strength; solution based polymers expensive; some polymers lack adhesion-bad in soil stabilization	low	9
polymer: methylmethacrylate + benzoyl peroxide		volcanic tuff	test specimens fr block sample	X		uniaxial compression		injected & liquid impreg	str incr - greater with impregnation; low incr in E; failure occurs w/ larger deformatn in tr sample	need more investigation of 1) mechanical characterization of tuff 2) optimization of process to be more economical and technol. advanced	?	15
polyelectrolytes: Na poly el, Ca salt, copolymers	.05-.1 % soil by wt	clay; silt; silty sand		X		floc efficiency & sed density; hydraulic stab; freeze-thaw; wet-dry; water retention; permeability		mixed " " " " " "	resis to hydr breakdown decr; particle size incr; resis to fr/th incr; permeability decr	object of study to establish standardized tests but no single one found to evaluate efficacy; soil type & physical conditions.soil subjected to influence improvemt and maint of soil structure	?	5
modified polymer poly(vinyl alcohol)	various	loess; loess-type kaolin & montmor clays		X		examination of micro-aggregate composition of soil	15 days	injected or mixed	degree of aggregation incr; water resistance incr;resistant to cyclic wet/drying, & long term soaking	high water absorption remains after treatment: material is porous	?	84
polymer hydrogel (Perma-soil)		silty clay; sandy clay; clay		X		pH; AL; compaction; uncon compression; consolidation; penetration		mixed	soils become nonplastic; wopt incr & dmax decr except for clay; gen str incr w/incr in cure time & % treatmt; compressibility decr, sett potential decr; penetration decr;	clay alone needed more treatment than other soils; reaction rate faster than that of lime; penetration dependent upon moisture content;	?	81
		sandy clay; clay; other	compacted in situ	X		street repair; penetration	immed, 1 hr, months	mixed	str incr, penetration decr; no subsidence or deterioration of repair apparent	evaluating str in field has some shortcomings; slower curing times important consideration for placing backfill in field		

RESINS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
resins	various	sand; clay	compacted	X		penetration;	3,6,24 hrs	mixed	str incr; resins for further testing chosen;	difficulty in compaction due to wetness of material, bentonite added to some of the soils to reduce moisture as w incr, str decr;	inject: ? mix: high	61
						compressive str;	24 hrs	"	str incr; opt resin content found for further testing;			
						flexural str;	up to 24 hr	"	flexural str incr;	failed at relatively low deformations;		
						shear str;	"	"	shear str incr;			
						depth of cure;	24 hrs	percolated	very little penetration;	no worthwhile depth of penetration in either soil;		
						environ factors:		mixed				
						1. water immer: penetration;	1 & 7 days imm		clay pen resis incr, sand pen resis decr;	resins superior to conventional methods because of rate of stabilization and strength attained; gen immersion caused a slow down in rate of initial curing;		
						compr str;	24 hr + 1, 2,3 wks imm		clay str decr, sand retained str;			
						2. temp effects: penetration;	24 hrs		pen resis incr & decr;	temp changes do not effect stress-strain characteristics; more research is necessary: 1. optimize effectiveness of best performing resins, 2. increase flexibility, 3. lower the cost, 4. dynamic loading, 5. field testing-pavement strips under repeated loads		
						compr str;			str incr;			
						3. freeze/thaw;			as # cycles incr, sand str incr, clay str decr;			
						4. diff w for clay			str incr & decr as w incr			
resin		sand	compacted	X		compaction; penetration; freeze-thaw; soak	3,6,24 hrs " 24 hrs 24 hrs+48 hrs soaked		strength incr	included screening of resins for further testing; preliminary report only	inject: ? mix: high	80
carb resin +ammonium chloride hardener		silty sand; clay soils	liquified; satur in situ		X	creation of injected retaining piles		injected	no deform or damage since work completed	formula can be refined for various climatic & weather conditions if necess.	inject: ? mix: high	64
niline urfural	1,2 % dry wt of soil	ion clays: Na,K, H,Al,Fe,Mg,Ca	compacted	X		compressive str; freeze/thaw; wet/dry	7D; 7D+7D imm; 7Dimm + 1,4 cycles		mod Proctor str > std Proctor str (tr or untr); imm str decr; str decr w/fr/th; str incr w/ wet/dry	strength tests run on specimens w/and w/o freeze/thaw and wet/dry for 1 and 4 cycles; test methods must be carefully analyzed with respect to pertinent physical and/or physico-chemical phenomena involved;	inject: low mix: ?	72
esins;		sandy soils;							facil comp, prev fr;	gen, need more investigations, problems include mixing equip, behavior of treated soil; fills voids;	inject: low unless in shear zone	33

RESINS (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
urea-form resin		dry & sat sands		X		load controlled compression test		injected	resistant to dyn stresses	quality control and equipment need improvement; specifics on injection and gel times	?	38
carbamide form resin		sandy soils	in situ		X		7 days	injected	mod resin released less form into air	must develop nontoxic resin; must test amt of form. passing into air	?	58
carbamide form resin + oxalic acid		sands, sandy soils	in situ		X	prevention of diff. settlement		injected	strength incr, diff. sett halted	stab soil is extension of foundation; allows proper distrib of load	?	34
aniline-furfural	0 to 12%	loess	compacted	X		uncon compr; AL; fr/th; wet/dry;	10 days & 10 days + 24 hr imm; 1,2,3,4,6,9, 10 cycles	mixed	gen, as % a-f incr, imm str incr, PI decr, dmax & wopt decr; unimm str>imm str; gen str decr w/fr/th & w/d on 1st cyc, then stay const	standard methods for evaluating effectiveness of chemicals not established, not comparable with field performance so cannot predict field results; a-f appeared a good waterproofer - hard to mix AL samples with water; toxicity and cost discussed		12
carb. resin + oxalic ac		*	from hardened soil in test pit	X		uniaxial compression				work proceeding on resinifacation of sandy loams; successful in many applications	inject: ? mix: high	22
calcium acrylate	4-25% of dry soil wt	sandy soils		X		AL & compaction		mixed	tensile str incr as % incr, wopt incr, dmax incr, AL decr	Ca acrylate good - use for membranes	mix: high	33
resin;	up to 10%	sandy loam;	compacted	X		strength; water resistance;		*	str and water resis depend on treatment level;	further, more systematic studies of the more promising chemicals advised; must look at economics; need to study bonding and waterproofing agents		97
resin (complex salt of abietic acid	.2, .5% by dry wt of soil	various	compacted	X		CBR;	2 day oven + 24 hr cap abs + 4 days imm	mixed	CBR incr for all soils; gen, more %, more effective; expansion decr; water absorption	need to run field tests now that lab tests have been completed; amount and rate of water absorbed decr; mainly a water proofer, does not add cohesion so not good on noncohesive soils	low	96

SALTS

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
salt		quick clay	undisturbed	X		diffusion of KCl	85 days		sensitivity decr shear strength incr diff depth 30 cm	diffusion using slaked lime does not seem practical; field project begun to investigate use of salts	? in soft clay	76
						diffusion of FeCl2	"		sensitivity decr shear strength decr diff depth 20 cm			
						diffusion of FeCl3	"		sensitivity decr shear strength decr diff depth 24 cm			
						diffusion of AlCl3	"		sensitivity decr shear strength incr diff depth 28 cm			
rock salt	6-18 lb salt/ton	sand; sandy loams	compacted in situ		X	density; moisture content; salt content; surface roughness; rutting measurements	up to 9 years	mixed	salt cont decr w/time; more salt, better perfornc, surf rough const over time, more rutting w/more fines & more salt	no detrimental effects from salt on asphalt; no construction probs encountered	low	11
sodium chloride		various	compacted in situ		X	road base stabilization		mixed	aggregate retention good; tendency to form frost boils decr	summary of cases using salt in Iowa; varied results, gen good; other projects underway at Iowa Engineering Experiment Station	low	39
sodium chloride+ lime	lime: 2,4,8% salt: 1,2,3% by dry soil wt	sand+clay (kaolin or Ca-montmorill)	compacted	X		uncon compr str	7, 28 days	mixed	gen salt = incr in d & wopt decr; kaol: 7D: no change 28D: str incr for greater lime, up to 1% salt, greater % fines mont: 7D: see 28D 28D: str incr for greater lime, up to 1% salt, less % fines gen 28D>7D for mont	salt restores loss in density due to lime; strength gain=f(clay content, %salt, %lime, cure time)	no better than lime alone	12
calcium chloride	0 - 2%, 4%	clay	compacted	X		compaction: dmax		mixed	dmax incr	CaCl2 good for Na montmorillonite; wanted to study effects pf CaCl2 on pure ion types of pure clay minerals	low	43
calcium chloride		unspecified		X		plasticity; unspecified			PI gen decr with incr CaCl2; freezing pt of soil water lowered	general summary paper	low	47

SALTS (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
fatty quat ammonium salt	.1% and up	silt loam; clay loam	aggregates	X		% of water stable aggregates;	2 days + 2 hrs imm + 24 hrs drying	mixed	water stability incr up to .1%; str incr when soaked in water for extended pds;	variations in flocc property = f(pH of soil, conc and types of salts in soil, mixing proportions of soil and fatty quat ammon salt); need to evaluate the the various types commercially available	?	18
						exp/cont; capillarity		" "	exp/cont tendency decr; capillary conductivity decr			
fatty quat ammonium chloride;	up to .5%	plastic clay	compacted	X		compaction; uncon compression;	7 days; + 6 days imm	mixed	no change in wopt, dmax; gen, more chem = more str;	nontoxic, waterproofer; generally compressive strength requirements not satisfied so may need to use additives	inject: ? mix: ?	73
						AL; capillary absorptn;	24 hrs, 8 days		PI decr for both cures; rate/amt of cap abs decr;			
fatty quat ammon chl + lime & + PC		"	"	X		uncon compression;	7 days; + 6 days imm		str incr w/sm amts of lime;			73
					X	road test sections			borne traffic w/no sig distress; w/lime, gained str with time	problems in placing chemical/soil in field; lab results hard to compare to field results		
quat amm chloride + additives;	0-8% qac + .6% additives	loess	compacted	X		uncon compr;	7 days w/& w/o 24 hr imm	mixed	unimm str decr; imm str incr to .2% additive, then str decr; all samples slaked in water			121
salts: NaCl, KCl, FeCl3, AlCl3, MgCl2 CaCl2		quick clay	remolded	X		AL fallcone - shear str	17 hrs		LL,PL incr; shear str incr	NaCl least effect on LL, PL, str & Al(OH)3 greatest effect; effectiveness of salt depends on cation - Al3+ most effectv for incr in sh str, LL; KCl had greater effect than NaCl	inject & diff: suitable for soft clays?	77
gels: Fe(OH)3 Al(OH)3		"	"	X		shear str chemical analysis	17 hrs + 26 days		same or more str than 17 hr cure			
calcium chloride; sodium chloride;	.5-2%	soil aggregate mix: glac till + gravel + silty clay loam	compacted	X		moisture-density; CBR; AL; moisture retention	m-d 5 min CBR immed & 4 days imm	mixed	gen dmax incr (CaCl, mol opt at 1%); str incr for CaCl, lign; str incr or decr for others depending on trtmt amt; no sig changes in PI for CaCl, NaCl;	recommendations to continue studies; cannot directly compare results of moisture retention for different chemicals; CaCl most effective on dmax.	low	40

SILICATES

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
sodium silicate	upt to 7% dry soil wt	clay (minerals);	briquettes	X		crushing of bricks;	0, 15 days	mixed	kaolin: resis to crushing incr; illite: "; mont: no gen trends	reaction between clay and sodium silicate takes place in moist conditions - dry aging did not strengthen briquettes;		127
		soils: silt loam; sandy loam; clay	briquettes	X		"		"	clay: PI & vol shrinkage decr; degree aggregation incr; crushing resis incr to 3.5% sod sil	1% or more of the sodium silicate dissolved organic matter;		
									silt loam: no effect, except aggregation incr;	sodium silicate not effective with all soils;		
									sand loam: PI decr a bit	sand loam solidified, did not aggregate		
iron ox. + sodium silicate	2-10% by wt of tot mixt	clays	compacted	X		examine physical & mech. properties	7 days	mixed	treated strength > untreated	patent application	inject: ? mix: high	27
sodium silicate		clayey loam; silty clays	sat in situ		X	stabilize foundatn soils under bldgs		injected w/CO2	str incr	cost comparison with conventional underpinning & this more economical	inject: ? mix: high	30
sodium silicate solution		loesslike clayey soils which slump	in situ		X	prevention of slump type settlement		injected	success in stab foundatn	CO2 gas used in injection process; good for industrial & residential foundations	inject: ? mix: high	29
sodium silicate;		sandy soils	in situ		X	prevention of sett of adjacent structure; stabilize soils beneath foundations		injected	settlement prevented	work proceeding on resinifacation of sandy loams; successful in many applications	inject: ? mix: high	22
silico-natrium soln		loess	in situ		X	prevention of diff. settlement		injected	diff sett halted		?	57
sodium silicate;		sandy soils;								gen, need more investigations, problems include mixing equip, behavior of treated soil; fills voids;	inject: low unless in shear zone	33

SILICATES (cont.)

1 Chemical	2 Treatment Level	3 Soil Type	4 Soil State	5 Lab Test	6 Field Test	7 Test Type	8 Cure Time	9 Method of Application	10 Test Results	11 Author's Comments	12 Slope Stabilization Potential	13 Ref. No.
grout: Na silicate + formamide + water	0,30,50,70% Na sil; 0,6,9,12% formamide	sand	sat samples at controlled densities	X		strength (tx, uncon compr)	1 to 220 days	injected	peak str and stiffness incr w/incr in % silicate	grout components must be carefully balanced to get desired results		116
					X	inject grout bulbs	30 days	"				
sodium silicate					X	stab effectvnss after water soak		soaked (perc)	str>than soil soaked in water	loess can be stabilized w/out introducing a binder	inject: ? mix: high (silty soils)	59
sodium silicate;	8-14%	various	compacted	X		direct compression;	? dry, dry + imm	mixed	sand str>clay str (of tr soils);	waterproofing agent needed in addition to sodium silicate;	inject: ? mix: high	97
	8%					effect of diff cure times & methods;			str not retained > 7 hrs, disintegration in 24 hrs;		(sils & resins)	
sod sil + salts;	8% sod sil	beach sand; find sandy loam; silt;		X		load sustaining power;	imm	"	chems pen silt, loam partially; gen salt cause str decr;	further, more systematic studies of the more promising chemicals advised; must look at economics; need to study bonding and waterproofing agents		
sod sil + CaCl2; + sulf acid;	various	sand;		X		compression;	imm	"	as CaCl2 incr str incr; sulf acid cause str decr, water resis incr;			
sod sil + sod alumnt;	"	sand; sandy loam;		X		different application methods;		"	separate mixing better; at once set time prob;			

ABBREVIATIONS USED - TABLE 2

amt	amount
asph	asphalt
AL	Atterberg limits
anal	analysis
ammon	ammonium
cmpds	compounds
comp	compaction
chng	change
const	constant
chem	chemicals
cont	contraction
compr	compression
cap abs	capillary absorption
CBR	California Bearing Ratio
decr	decrease
D	day(s)
diff	differential
diff	different
diff	diffuse(d)
dyn	dynamic
erosn	erosion
exp	expansion
facil	facilitate
fr	freezing
form	formaldehyde
fr/th	freeze/thaw
gen	generally
gyp	gypsum
hr/hrs	hour(s)
incr	increase
imm	immersed
immed	immediate
kaol	kaolinite
LL	liquid limit
lig	lignin
mol	molasses
mo(s)	month(s)
mont	montmorillonite
m-d	moisture-density test
mvemt	movement
mat'l	material
mod	modified
max	maximum
opt	optimum
PC	portland cement
propor	proportional
pt	point
PI	plastic index
PL	plastic limit
prev	prevent(s)
pa	phosphoric acid
pen	penetration
quat	quaternary
resis	resistance
sm	small
stab	stabilize
sulf	sulfuric
sig	significant
str	strength
std	standard
sett	settlement
temp	temperature
tr	treated
trtmt	treatment
untr	untreated
unimm	unimmersed
uncon	unconfined
vol	volume
w	water content
weath	weathering
γ_{dmax}	maximum dry density
w/d	wet/dry
w/	with

TABLE 3 PROPRIETARY CHEMICAL STABILIZERS

Company	Product	Chemical	Intended Use	Intended Soils	Method of Application	Cure Time	Treatment Level	Stabilization Potential
Ion Tech, Inc	Unidentified chemicals	ionic solution	stop active landslides	clays	injection; diffusion	unspec	unspec	uncertain
American Consolid Inc.	Consolid 444 & Conservex	petroleum distillates	load bearing foundation for roads	cohesive; semi-cohesive	mixing	24 to 48 hours	C444: 6.25 g/ 100 yd2 Cons: 25 g/ 100 yd2	?, cannot be injected
Soil Stabilization Products Co	BIO CAT 300-1	biochemical formulation	stab soils for roads, slopes	any	mixing		1 l/1.8 m3	unknown
American Soil Technology Corp	ECO 550	polymers	road bases, erosn control	any	mixing	72 to 96 hours	1 g/15 ft2/4in depth	unknown
	ECO 110	resin emulsion	erosn control	any	spraying	a few hours		low
Chevron	SUBIND	inorganic sulfur form	road bases, dust control	semi-cohesive	spraying; mixing		0.9-9.0 l/m2	unknown
	SUFERM	inorg & org chemicals	stab earthen structures	"	"		0.25-0.75 l/m2	unknown
Stabilizer	Stabilizer	organic mat'ls ?	erosn control	topsoil, sand	mixing			low
Central Chemical Company	Cla-Pak, Cla-Set, Cla-Chek	Unknown	base stab, erosn control	clays & silts	mixing; spraying		clay: up to 25 g/ft/mile silt: up to 6 g/ft/mile	inject: unknown
ECO Geochemical Consulting Ltd		various grouts	many uses	any				
Kansai Engineering Co., Ltd	GEOSTA	inorg soln	roads, soft ground, erosn control	any				unknown
Takenaka Komuten Co., Ltd Takenaka Doboku Co., Ltd	DCM	cement slurry	stab deep foundations	clayey soils	mixing		depends on soil	has potential if mixed
Earth Science Products Corp	Condor SS	sulfonated oil	road stab, embankments	silts, clays	mixing; injected			has potential if mixed

virtually essential for success in the case of fine-grained soils, more viscous formulations can be used than would be the case for grouting. This means that somewhat higher strengths should be attainable than would be possible by injection alone.

A comprehensive summary of information about chemical grouts and their properties, including some information about toxicity, is given in Chemical Grouting by Reuben H. Karol, Marcel Dekker, Inc., New York, 1983 (Reference 92).

Like the resins, sodium silicate, the other promising chemical class for chemical stabilization of slopes, either fills the pores of the soil and/or cements the soil particles. It has been both injected and mixed. Again, the literature provides little information on the properties and compositions of the sodium silicate solutions viewed as promising for slope stabilization. However, extensive information is available about the properties of silicate grouts; e.g., Karol (1983).

A listing of sources of grout chemicals is given in Appendix 3. The listed individuals and organizations should be able to provide information and materials about compositions, properties, handling, environmental impacts, availability and costs of chemicals for use in slope stabilization.

The resins with potential for slope stabilization can be used in sandy or clayey soils. They can cause an increase in the strength and stability and a reduction in the swelling potential. Resins have the advantage of a faster rate of stabilization than many other chemicals because of short set times, yet they can be costly. Various types of resins have been tested, natural and synthetic, including carbamide, urea-formaldehyde, and aniline-furfural.

Although listed in Table 2 as non-proprietary materials, silicates are available also in a range of proprietary formulations. Silicate grouts have a long history of successful use in sands. Provided they are adequately mixed with the soil, they may be equally useful in fine-grained soils as well.

Other chemical classes that have been studied for the stabilization of soils include phosphoric acid, lignins, salts, hydroxides, polymers, and large organic cations. Phosphoric acid has generally been restricted to treatment of clay or loess soils. Lignins, salts, and hydroxides have been shown to give some improvement in treated soil properties under some conditions. The potential of these chemicals for stabilization of slopes is uncertain, as investigations so far have been mainly relative only to road applications;however, none seem capable of the strength improvement obtainable with either resins or silicates.

D. Techniques for In-Situ Mixing

As noted earlier simple injection of chemicals into unstable slopes of fine-grained soil is not likely to be successful for stabilization because of the need for distribution of the chemical throughout the unstable zone. There are, however, three relatively new techniques that may be suitable for economical and effective slope treatment. They are (1) deep in-place mixing, (2) jet grouting, and (3) impulse injection. Deep mixing and jet grouting are described by Mitchell (1981), reference 55, and brief descriptions follow.

Deep chemical mixing is performed in situ. An admixture, generally lime or portland cement in past applications, is mixed with the soil to form stabilized columns or walls. A measured amount of stabilizer is fed

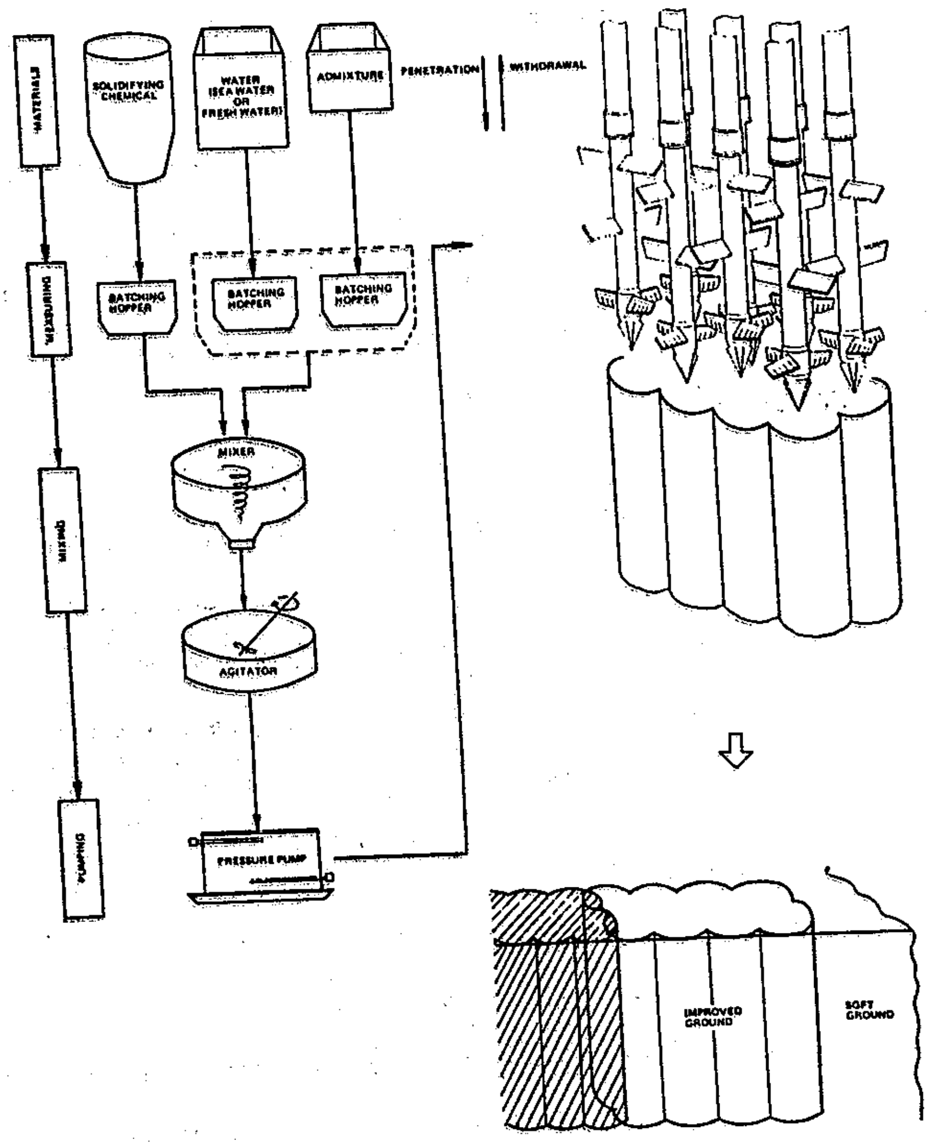


FIGURE 1 DEEP CHEMICAL MIXING

into the soil to be stabilized through rotary drills equipped with special auger bits to advance to the desired depth and to mix the admixture and soil thoroughly during withdrawal. Figure 1 shows the process schematically. The process could be used alone or in conjunction with other stabilization methods to prevent the movement of slopes. An arrangement of columns, groups of columns, in-situ walls, or treated buttresses can be designed to yield the needed factor of safety.

Jet grouting is a process that fractures and erodes the soil around a drilled hole by high pressure (several thousand psi) grout jets directed horizontally away from the drill rod. Grout slurry is injected through the jet pipe and mixed with the disturbed soil. Stabilized soil columns are formed by simultaneously lifting and rotating the drill rod while jetting, Figure 2. Jet grouting can be used in both cohesive and noncohesive soils. Portland cement has generally been used as the admixture; however, chemicals could be injected as well. This method can be carried out vertically, or at an angle to stabilize a slope, as shown in Figure 3.

In a technique recently developed by Underground Technologies of Brentwood, CA, a rapid series of pulsed injections under very high pressure is used to mix a stabilizer with the soil. An accumulator is used to develop injection pressures of several thousand psi. The injected material breaks down and mixes with the soil, producing a high strength zone. Columns and walls can be produced. Insufficient data are available so far to define the levels of improvement that are possible; however, the method has been used successfully for strengthening the foundations of towers and poles.

A list of companies and contractors operating in the U.S.A. that do deep mixing, jet grouting, and impulse injection is given in Appendix 4.

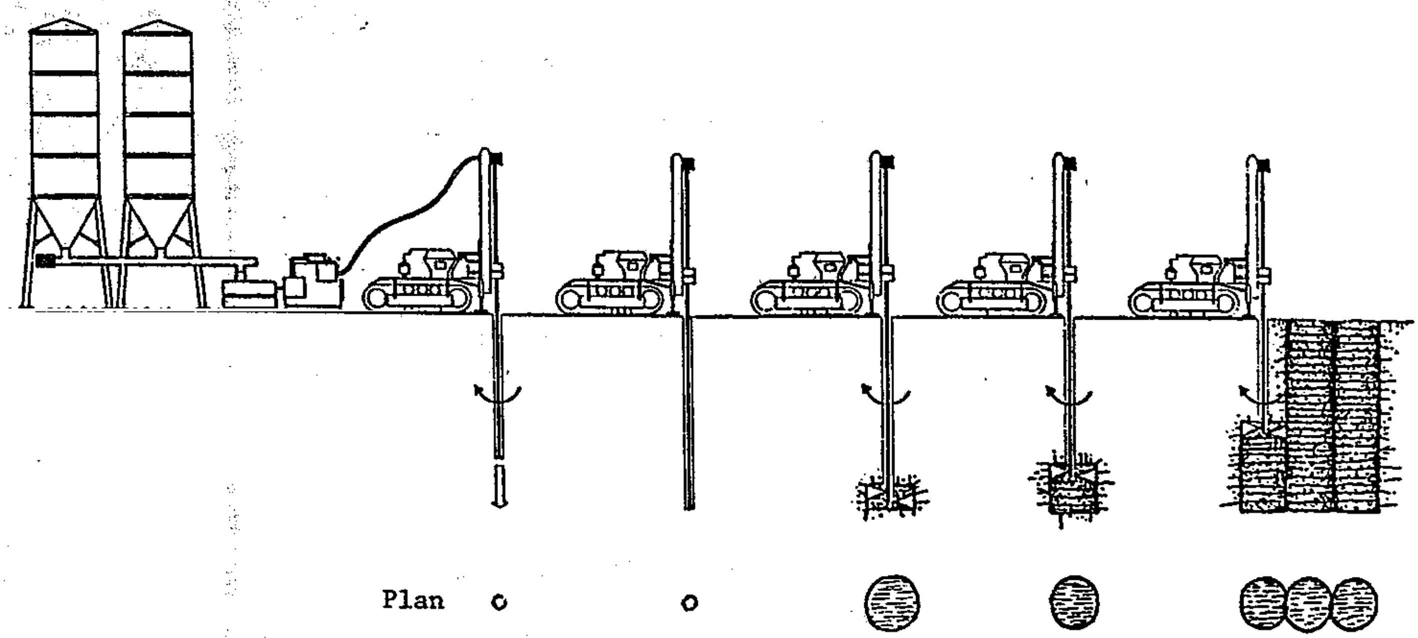


FIGURE 2 JET GROUTING: FORMATION OF STABILIZED SOIL COLUMNS

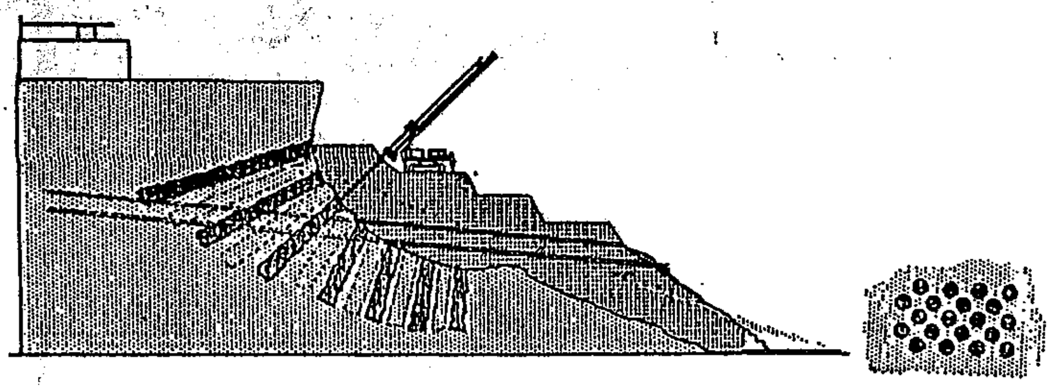


FIGURE 3 HILLSIDE STABILIZATION BY JET GROUTING

E. Proprietary Materials and Techniques for Stabilization (Table 3)

Deep mixing methods for stabilization of soft clayey or sandy soils, using a cement slurry with chemical additives have been developed. The strength of the soil is increased while the permeability is lowered. S.M.W. Seiko Co., Ltd. (Redwood City, CA) is among the first companies in the U.S.A. to use this method to strengthen soil. The first major application of this method in the U.S.A. is for the stabilization of liquefiable sands and gravels at Jackson Lake, Wyoming during 1987-88.

The Claypak system, developed by the Central Chemical Co., incorporates several products into clays or silts. The wet bearing strength of the soil is increased, and the plasticity index and potential for expansion and contraction are decreased. According to the available information the soil must not be saturated. No particular lab tests or methods are recommended, just those normally used and/or preferred. The products are reported to increase the friction between the particles and the migration rate of water through the saturated soil. To stabilize a landslide it would be necessary to know the slide plane location and size. These products are not intended by the manufacturer to be the sole method of correction, but used in addition to conventional correction methods. As the Clay-Pak chemicals are acidic, they are difficult to handle.

Ion exchange was proposed in the Iontech system for slope stabilization, developed several years ago, but apparently no longer available. An ionic solution, the make-up of which depends upon the soil to be stabilized, is injected into hillsides to increase the shear strength of clays. Laboratory tests must be performed prior to stabilization to identify the soil in question and to choose the most appropriate chemical. Test specimens ideally should come from the slip surface. Application is simple and non-toxic chemicals are used. To stabilize hillsides, the solution must come into contact with existing and potential slip surfaces. The effectiveness of this technique has not been definitely established.

American Consolid, Inc. proposes the use of a two step liquid chemical stabilization process that can be used on all cohesive or semi-cohesive soils as long as they are mixable. The stabilizers, Consolid 444 and Conservex, are petroleum distillates that are mixed into the soil; injection is not recommended. This process increases the bearing strength and CBR of a soil, decreases its water sensitivity, and allows better permeability control. In addition, it reportedly is less expensive to use than conventional admixtures and is non-toxic and non-polluting.

Condor SS is a sulfonated oil product distributed by the Earth Science Products Corporation. The soil to be stabilized must contain at least 30% fines. The Atterberg limits, moisture content and density are used to determine the amount of chemical required. This product increases the shear strength, bearing strength, and density of the soil in question. It reduces the capillarity, organic content, and optimum moisture content of the soil. Condor SS is corrosive and must be handled carefully during application.

BIO CAT 300-1 is an environmentally acceptable, water soluble chemical composition marketed by the Soil Stabilization Products Company. Reportedly, it improves clays, silts and sands by increasing the strength, CBR, and the water resistance of the soil. It decreases the potential for frost heave and the optimum water content of the soil. Laboratory tests, including strength, resistance to expansion, permeability, and shrink/swell potential, are used to check the performance of the chemical with each soil prior to field application. Attention must be paid to the temperature during use and the cure procedure.

ALPHABETICAL LISTING OF REFERENCE KEYWORDS

NUMERICAL LISTING OF REFERENCE KEYWORDS

1	dispersants	29	sodium hydroxide
2	bitumens	30	mixed in situ
3	portland cement	31	voids filled
4	historical review/ literature review	32	sulfates
5	resins	33	stabilization mechanisms discussed
6	lime	34	ammonium chloride
7	ion exchange for stabilization	35	hydroxy-aluminum
8	sodium silicate	36	water glass
9	iron oxide	37	sulfuric acid
10	quaternary amines	38	phosphate rock
11	pozzolan - flyash	39	hydrochloric acid
12	inorganic bases	40	molasses
13	pollution due to chem. stabilization	41	waterproofing agent
14	industrial waste/refuse	42	case history
15	reference chart	43	lab tests
16	experiments & results	44	field tests
17	salts	45	diffused
18	lignin, chrome-lignin, lignosulfonates	46	percolated
19	aggregants	47	multivalent cations, organic cations
20	phosphoric acid	48	aniline furfural
21	grout	49	hydroxides
22	calcium chloride	50	creeping mass
23	polymers	51	slickensides
24	hydrofluoric acid	52	known failure plane
25	silicones	53	gypsum/slag
26	injection process	54	sprayed
27	solution used	55	sodium acid abietate
28	cementing of soil particles	56	rosins
		57	petroleum derivatives/distillates

ALPHABETICAL LISTING OF REFERENCES ON CHEMICAL STABILIZATION OF SOILS

Reference Listing Format:
art no
author
art title
publication and date
location
key words (see separate listing)

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Highway Research Board Bulletin n 241 1960 p 1
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Highway Research Board Bulletin n 129 1956 p 10
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Sao Paulo
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Fugitive Dust Control for Haulage Roads & Tailing Basins
U.S. Dept of the Interior, Bureau of Mines Rpt of Investigations 9069, 1987
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Appendix 1

Solicitations for Information on Chemical Stabilization of Slopes

Two sets of letters were mailed requesting information pertinent to the study. The first set of letters was sent to the Geotechnical Engineers of the Department of Transportation of each state and of each Federal Highway Administration Region. Responses, in the form of a letter or phone call, were received from slightly over 50% of the people contacted. Of the 33 responses, 25 indicated no experience with chemicals as stabilizers for slopes. Six states had experimented with lime only and one with cement only. One state, Iowa, has experimented with several admixtures, including asphalt, gypsum, sulfides and silica gels, all of which proved to be unsuccessful for various reasons.

The second set of letters was sent to various manufacturers or distributors asking about specific soil stabilization products. Ten organizations were contacted. Four of these responded, usually sending a company brochure and/or additional information on the product in question.

An example of each of the two groups of letters used from solicitation of information on chemical slope stabilization is given on the following pages.

UNIVERSITY OF CALIFORNIA, BERKELEY

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CIVIL ENGINEERING
Geotechnical Engineering
440 Davis Hall

BERKELEY, CALIFORNIA 94720

June 12, 1987

Dow Chemical Co.
2030 Dow Center
Midland, MI 48640

Dear Sirs:

We are presently engaged in a project under the sponsorship of the California Department of Transportation on the chemical stabilization of landslides. Our specific objective is to identify and evaluate promising and potentially useful materials and methods, with emphasis on stabilizers other than cement and lime. The major focus is on methods for improving hillside stability and stopping creep movements. If promising candidate materials can be identified, then recommendations will be formulated for field evaluation tests to be done by Caltrans.

I am writing to you because it has come to our attention that your company has developed two products, Peladow and Terbec C-7, which may be of interest to this study. We have already assembled most of the readily available literature from personal files and the usual library sources. Information on your products, however, has not been found during our search thus far. I would be most grateful if you could make available to us any literature on the products, especially technical information giving the results of laboratory or field tests performed using these chemicals.

Thank you very much for your help.

Sincerely yours,

James K. Mitchell
Professor of
Civil Engineering

JKM/edb

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CIVIL ENGINEERING
Geotechnical Engineering
440 Davis Hall

BERKELEY, CALIFORNIA 94720

March 13, 1987

Mr. Carl Gottschall
Geotechnical & Const. Engineer
Federal Highway Administration,
HEO-01 Leo W. O'Brien Fed. Bldg.,
Room 729 Clinton Ave. and N. Pearl St.
Albany, New York 12207

Dear Mr. Gottschall:

We are presently engaged in a project under the sponsorship of the California Department of Transportation on the chemical stabilization of landslides. Our specific objective is to identify and evaluate promising and potentially useful materials and methods, with emphasis on stabilizers other than cement and lime. The major focus is on methods for improving hillside stability and stopping creep movements. If promising candidate materials can be identified, then recommendations will be formulated for field evaluation tests to be done by Caltrans.

I am writing to you to request your assistance in identifying any pertinent information on chemical stabilization that may bear on this problem, but which may have been overlooked or not easily available. We have already assembled most of the readily available literature from personal files and the usual library sources. There may be, however, project reports, chemical evaluations, or other information that has not made its way into the open literature, but which would be useful for this study. If you know of any and could make it available, I will be most grateful. If you know of any leads that might be followed to such information or have information about new chemicals, it would be helpful as well. If you would rather call than write, my phone number is (415) 643-8624.

Thanks very much for your help.

Sincerely yours,

James K. Mitchell
Professor of
Civil Engineering

JKM:edb

Appendix 2

Manufacturers and Distributors of Proprietary Chemical Stabilizers

Ion Tech, Inc.
Company no longer exists

American Consolid Inc.
5328 Tremont Ave.
Davenport, IA 52807
(319) 386-0620
Paul K. Raiford, Jr., Vice President

Soil Stabilization Products Company
P.O. Box 2779
Merced, CA 95344
(209) 383-3296
Robert B. Randolph

American Soil Technology Corporation
945 Sunset Drive
Costa Mesa, CA 92627-4409
(714) 722-2900
Dick Peckenpaugh

Chevron Chemical Company
Sulfur Products Division
575 Market Street
San Francisco, CA 94105
W.G. Toland, Vice President & General Manager

Stabilizer
1522 North 35th Street
Phoenix, AZ 85008
(602) 273-6244
Tim Myers

The Central Chemical Company
1407 East Olive Avenue
Fresno, CA 9372f8
(209) 268-0241

ECO Geochemical Consulting Ltd.
301-336 5th Avenue North
Saskatoon, Sask.
Canada S7K 2P4
(306) 242-3323
Alex Naudts

Kansai Engineering Co., Ltd.
Post. No. 617 47-3,
Imazato Fukeno-Cho,
Nagaokakyo-City Kyoto-Pref.
Japan
(075) 954-1221

Takenaka Doboku Co., Ltd.
21-1, 8-chome, Ginza,
Chuo-ku, Tokyo, 104
Japan
(03) 542-6321

Earth Science Products Corp.
1960 S.W. 16th Avenue
Portland, OR 97201
Richard C. Gearhart, President

Appendix 3

Sources of Soil Grouting Materials, Resins, and Silicates

Avanti International
1275 Space Park Drive
Houston, Texas 77058
713-333-5430
Contact: F. David Magill
(Q-SEAL Acrylamides, urethanes)

Celtite, Inc.
Cleveland, Ohio 44133
216-237-3232
Contact: Tony Plaisted
(Polyurethanes, phenolic resins, sodium silicate hardeners)

Federal Bentonite
1002 Greenfield Road
Montgomery, Illinois 60538
910-232-0759
Contact: Bruce Beattie

International Minerals & Chemical Corp.
666 Garland Place
Des Plaines, Illinois 60016
312-296-0600
(Bentonite)

Penetryn Restoration
Division of BPR Corporation
Knoxville, Tennessee
(Phenolic resins, sodium silicate hardeners)

U.S. Grout Corporation
401 Stillston Road
Fairfield, Connecticut 06430
203-336-7900
(Portland Cement Grouts, bentonite)

American Colloid Company
Environmental Products Div.
5100 Suffield Court
Skokie, Illinois 60077
312-966-5720
(Bentonite)

Cues, Inc.
3501 Vineland Road
Orlando, Florida 32805
305-849-0190
(AM-9 only)

Halliburton Services
Duncan, Oklahoma 73533
405-251-3760
(Jet Grouting, Bentonite Products)

Mobay Chemical Corporation
Plastics and Coatings Div.
Pittsburgh, PA 15205
412-788-1458
Contact: Kirk McCabe
(Resins, sodium silicate hardeners)

Reichold Chemicals, Inc.
RCI Building
White Plains, New York 10602
617-475-6600
(Resins, silicate hardeners)

3M Center
Adhesives, Coatings & Sealers
Division
St. Paul, Minnesota 55144
Contact: Joe Gasper
(Foams, urethanes)

Geochemical Corporation
162 Spencer Place
Ridgewood, New Jersey 07450
201-447-5525
Contact: William J. Clarke, Pres.
(Resin, AC-400 Grout, acrylate monomers)

Pressure Grout Company
125 South Linden Avenue
So. San Francisco, CA 94080
415-871-2244
Contact: H. R. Al-Alusi
(Chemical grouting)

SIROC Department
Raymond Concrete Pile, Division of
Raymond International Inc.
2 Pennsylvania Plaza
New York, NY 10001
(SIROC chemical grout, silicate formaldahyde)

PQ Corporation, Incorporated
801 Grayson
Berkeley, CA 94710
415-845-1048
(Silicates)

Dougherty Foundation Products, Inc.
P. O. Box 688
Franklin Lakes, NJ 07417
201-337-5748
(Jet grouting)

Appendix 4

Organizations that do Deep Mixing, Jet Grouting, and Impulse Injection

GKN Hayward Baker
1875 Mayfield Road
Odenton, MD 21113
(301) 551-8200
(Jet grouting)

S.M.W. Seiko, Inc.
100 Marine Parkway
Suite 350
Redwood City, CA 94065
(415) 591-9646
(Deep mixing)

Pressure Grout Company
125 South Linden Avenue
South San Francisco, CA 94080
(415) 871-2244
(Jet grouting)

Underground Technologies
P. O. Box 322
Brentwood, CA 94513
(415) 634-2688
(Impulse injection)

Haliburton Services
Duncan, Oklahoma 73533
(405) 251-3760
(Jet grouting)